Renewable and Sustainable Energy Reviews 14 (2010) 798–805

Contents lists available at ScienceDirect

Renewable and Sustainable Energy Reviews

journal homepage: www.elsevier.com/locate/rser

# Banana biomass as potential renewable energy resource: A Malaysian case study

Jing Yan Tock, Chin Lin Lai, Keat Teong Lee *, Kok Tat Tan, Subhash Bhatia

*School of Chemical Engineering, Engineering Campus, Universiti Sains Malaysia, 14300 Nibong Tebal, Seberang Perai Selatan, Pulau Pinang, Malaysia*

ARTICLE INFO

*Article history:*
Received 6 July 2009
Accepted 14 October 2009

*Keywords:*
Banana
Biomass
Energy

ABSTRACT

The world has been relying on fossil fuels as its primary source of energy. This unsustainable energy source is not going to last long and thus, gradual shift towards green renewable energy should be practiced. In Malaysia, even though fossil fuel dominates the energy production, renewable energies such as hydropower and biomass are gaining popularity due to the implementation of energy policies and greater understanding on the importance of green energy. Malaysia has been well endowed with natural resources in areas such as agriculture and forestry. Thus, with the availability of feedstock, biomass energy is practical to be conducted and oil palm topped the ranking as biomass source here because of its high production. However, new sources should be sought after as to avoid the over dependency on a single source. Hence, other agriculture biomass should be considered such as banana plant biomass. This paper will discuss on its potential as a new biomass source in Malaysia. Banana plant is chosen as the subject due to its availability, high growth rates, carbon neutrality and the fact that it bears fruit only once a lifetime. Conversion of the biomass to energy can be done via combustion, supercritical water gasification and digestion to produce thermal energy and biogas. The theoretical potential power generation calculated reached maximum of 950 MW meeting more than half of the renewable energy requirement in the Fifth Fuel Policy (Eighth Malaysia Plan 2001–2005). Thus, banana biomass is feasible as a source of renewable energy in Malaysia and also other similar tropical countries in the world.

© 2009 Elsevier Ltd. All rights reserved.

**Contents**



* Corresponding author. Tel.: +60 4 5996467; fax: +60 4 5941013.
*E-mail address:* chktlee@eng.usm.my (K.T. Lee).

1364-0321/$ – see front matter © 2009 Elsevier Ltd. All rights reserved.
doi:10.1016/j.rser.2009.10.010

## 1. Introduction

The world has been mainly relying on fossil fuels as its source of energy. However, this limited, nonrenewable energy source will not be able to sustain the growing need for energy for the next 100 years to come. The burning of fossil fuels tends to lead to severe environmental problems. The industrial revolution that began in the late 1700s brought forth the widespread use of fossil fuel. Since then, the concentration of carbon dioxide in the atmosphere has increased more than 30% and this amount increases by roughly 0.5% every year. Carbon dioxide, being a greenhouse gas, can cause global warming [1]. The increasing emission of greenhouse gasses leads to the rising global temperatures. This will disrupt the livelihood of hundreds of millions of people across the nation [2] and up to a million of species could go extinct [3] if the average global temperatures rise by more than 2 °C. This major catastrophe is rather inevitable if the global emissions do not start to fall within the next 20 years [4].

These are some of the main reasons that most countries are shifting towards green energy production, which includes wind energy, solar energy, hydropower, biofuel and biomass. For economical purposes, countries will opt for renewable energy that suits them most, depending on the geographical location, climate condition and availability of renewable sources. For example, insolation (solar radiation) in the Mojave Desert near Barstow in California, is very high and therefore, very suitable for solar power plants [5]. However, the high cost of this technology is one of the major drawbacks to commercialize it for wider application worldwide. On the other hand, China, which is surrounded by ample water source and mountains, is the greatest producer of hydroelectric power in the world. According to the Key World Energy Statistics from the International Energy Agency (IEA), China's hydroelectricity production amounts to around 14% of the world's production in 2006 [6]. However, construction of dams requires extensive logging and resettlement that can lead to the extinction of several flora and fauna species.

Looking into other alternative renewable energies, another source of energy is what our forefathers have been using since the dawn of the century – Biomass. This energy source if developed in a truly sustainable way can be the answer to the environmental issues and definitely a potential solution to climate change. Biomass takes in carbon dioxide from the atmosphere during their growth stages to compensate for the carbon produced when it is burnt. With this zero carbon emission, the use of biomass as one of the sustainable energy mix has great potential benefits. One of the major examples of biomass application is biofuel. Countries like Brazil, which is the biggest producer of sugarcane, is able to produce bioethanol from sugarcane. But there is an ongoing debate on whether our food supply should make way for energy. Thus, utilizing waste biomass for energy would be a better option. Zimbabwe has been conducting some research on energy production from crop residues. It was reported that crops, fruits and forestry residues have energy potential of 81.5, 4.9 and 44.3 PJ per year, respectively. This represents about 44% of the gross energy consumption in Zimbabwe [7]. Meanwhile, Australia has been delving into biomethane derived from banana waste. University of Queensland Researcher and Associate Professor Bill Clarke, supported by the Queensland Government though the Queensland Sustainable Energy Innovation Fund (QSEIF), Ergon Energy, and the Australian Banana Growers' Association Inc., uncovered the potential to produce biogas from banana waste using fed-batch digestion [8].

In Malaysia, biomass is also gaining increasing attention. Prior to this, the government has introduced the Fifth Fuel Policy in Eighth Malaysia Plan 2001–2005 [9]. Here, renewable energy was announced as the fifth fuel in the energy supply mix and targeted to be a significant contributor to the country's total electricity supply. Having this objective in mind, greater efforts are being undertaken to encourage the utilization of renewable resources, such as biomass, biogas, solar and mini-hydro, for energy generation. Of the efforts in promoting biomass energy is the Small Renewable Energy Power (SREP) Program launched in May 2001. These shifts towards green energy are further enhanced with the implementation of Energy Efficiency and Renewable Energy in Ninth Malaysia Plan 2006–2010. Here, the initiatives for energy efficiency and renewable energy put forth in the Eighth Malaysia Plan that focused on better utilization of energy resources are strengthened.

Malaysia has been endowed with natural resources in areas such as forestry and agriculture. In agriculture sector, oil palm trees are widely planted in Malaysia, thus it is not surprising that it is the major biomass source. The oil palm residue ranging from empty fruit bunches and fronds to the shell and mesocarp fibres can all be converted to energy sources via combustion, gasification and pyrolysis [10]. However, recent innovation in furniture production makes use of the waste palm oil fibres to produce furniture cushion. This leads to the competition of feedstock for energy production and furniture production. Apart from that, palm oil itself can also be converted into biodiesel. Energy generation from palm oil residue biomass is not much favorable as compared to palm oil itself. This scenario holds the potential for an increase global demand for this commodity. One of the major drawbacks of this application is the disruption of food-chain and the increase in crude palm oil (CPO) price [11]. With this fuel and food feud, generally, fuel production will be more favored as it fetches a better profit. Eventually, this will lead to inflation due to the increase in world palm oil price, a major edible oil source in the world. Therefore, alternative biomass source like crop residue is gaining popularity. A good example is rice husk, but rice husk cogeneration suffers from an image problem in Malaysia due to mixed and disappointing results in past projects. It remains to be seen that some of the successful projects that are coming about in Pendang, Kedah Darul Aman would be able to renew interest in this area [12].

Apart from palm oil and rice husks, other biomass sources from agriculture residues should be given a consideration as to not over depend on a single source. One of them is the banana plant biomass. Many people are not aware of the fact that after each banana plant gives forth its fruit; its banana-producing days are over [13]. Instead of disposing it or wasting it as organic fertilizer, a better way would be converting them into energy. After harvesting the fruit for consumption, the rest of the plant would be a source for biomass energy generation either in the form of thermal energy or biogas. A successful example of banana waste biogas generation has been done by Growcom, a Queensland based horticultural services company. Growcom decided to transform Dr Clarke's lab research into a commercial scale project in North Queensland, a location where bananas are far from scarce [8].

Until now, none has ever looked into energy production from banana residue in Malaysia. In conjunction to this, the potential of banana residues as a new renewable energy source in Malaysia will be discussed in this paper Thus, the main objective of this paper is to determine whether banana residue has the potential to be a biomass energy in Malaysia. This paper will discuss about the composition of the banana plant, the potential power that it is capable of generating using various methods as well as its advantages and challenges faced. A case study related to banana residues energy production will also be discussed.

## 2. Banana feedstock

Generally, bananas are found in abundance in tropical and subtropical areas. They are native to regions of Southeast Asia and

cultivated throughout the tropics. Banana is the common name for the herbaceous plants of the genus Musa and is cultivated mainly for its fruit. The total planted area of banana in Malaysia reached 33,704.2 ha in 2001 [14]. There are 25–80 species in the genus *Musa*, depending on the taxonomist. *Musa* is important not only for fruit production, but also has provided man with clothing, tools, and shelter prior to recorded history.

### 2.1. Cultivation

Banana plants are restricted to tropical or neartropical regions, roughly the area between latitudes 30°N and 30°S [15]. Within this band, there are varied climates with different lengths of dry season and different degrees and patterns of precipitation. A suitable banana climate is a mean temperature of 80 °F (26.67 °C) and mean rainfall of 4 in. (10 cm) per month. There should not be more than 3 months of dry season. Malaysia lies on the equatorial region with tropical climate metting this criteria. Generally, banana requires 10–12 months from planting to harvest. This short time spent for banana residue generation ensure the easy availability of banana energy feedstock. Commercially, banana is planted at a 2.5 m × 2.5 m spacing or 3 m × 3 m spacing giving rise to 1600 plants per hectare and 1100 plants per hectare, respectively [16]. Apart from that, they can be also planted together with other crop such as rubber trees, plam oil, cocoa and durian trees as co-crops. A row of banana plants can be planted alternately with those main crops mentioned at a spacing of 3 m × 3 m with the density of 700–900 plants per hectare.

### 2.2. Components

Banana plant being normally tall and fairly sturdy, often erroneously referred to as a "tree". It is a large herb, with succulent, very juicy stem which is a cylinder of leaf-petiole sheaths composed of long fibres and strongly overlapping called pseudostem. Banana plants range in height from 0.8 m to more than 7.5 m. Each pseudostem bears fruit only once before dying and being replaced by another pseudostem. The perennial portion of the plant which generates the new pseudostem is the rhizome. It may weigh several pounds and is often called a corm. It produces suckers, or vegetative shoots, which are thinned to 2 per plant—one "parent" sucker for fruiting and one "follower" to take the place of the parent after it fruits and dies back. It also produces roots and serves as a storage organ for the plant [17]. This pseudostem consists of concentric layers of leaf sheath and crown of large leaves which are among the largest of all plants. Generally 30 large leaves of 30–60 cm wide and up to 2 m long are produced in each plant [14].

Each pseudostem can produce a bunch of bananas. The banana fruit grows in hanging clusters with up to 20 fruit to a tier and 3–20 tiers to a bunch. The whole hanging clusters, known as a bunch weighs from 30 to 50 kg with fruit averages 125 g each of approximately 75% water content and 25% dry matter content. Each individual fruit has a protective outer layer which is the peel or skin and a fleshy edible inner portion. Both parts can be eaten raw or cooked and has a very high carbohydrate content and are valuable source of Vitamin B, Vitamin C and potassium [18]. Fruit reach harvest maturity in 90–120 days after flower opening. Banana plants have high yields of an average up to 50 tonnes per hectare and up to 40 tonnes for plantains [19].

Banana biomass studied here comprises of three main items which are the rejected fruits, the peels and the pseudostems. Feedstock derived from rejected bananas is approximately 30% of the total production. Apart from being rejected at the packing shed due to high consumer expectations on the quality, the remaining unsold rotten overripe fruits fall into this category as well. This type of feedstock is easily handled by cutting it into cubes and storing at a low temperature of 20 °C. A high yield of methane per unit weight of dry banana can be produced from the banana waste [20]. Besides using the rejected or spoilt bananas, banana peels are also a major consideration as a source of banana biomass feedstock. Banana is one of the major food crops in certain countries so large quantities of waste are often generated from the peels and this can cause serious problems if disposed indiscriminately. When decomposed, these wastes may produce noxious gases such as hydrogen sulphide, ammonia, etc. that can pose serious environmental hazards [21]. Thus turning them into biomass feedstock offers a better waste management option and also source of energy production. The banana peels are usually obtained or purchased in bulk from certain food processing plants, markets, food and beverage shops, etc. [21–23]. Since the pseudostem bears fruit only once before it dies down and replaced by new sprouts, this bulky portion therefore generates the largest amount of banana plant residue. Here, the crown of leaves is considered part of the pseudostem residues.

### 2.3. Current utilization

After harvesting the fruit for food, the pseudostem is traditionally wasted for which it is normally left in the soil plantation as organic fertilizer or mixed with the rejected fruits to make animal feed. Banana leaves are widely used as plates and for lining cooking pits and for wrapping food for cooking or storage. However, this will eventually turn into waste after it has served its purpose. Improved processes have made it possible to utilize banana fibre for many purposes such as paper, rope, table mats and handbags [15]. In Kerala, India, a craft type paper of good strength has been made from crushed, washed and dried banana pseudostems which yield 48–51% of unbleached pulp. This good quality paper is made by combining banana fibre with that of the betel nut husk (*Areca catechu* L.). However, Australian investigators hold that the yield of banana fibre is too low for extraction to be economical. Only 1–4 oz (28–113 g) can be obtained from 40 to 80 lbs (18–36 kg) of green pseudostems; 132 tonnes of green pseudostems would yield only 1 tonne of paper.

Another current innovation in utilizing banana residue is the banana textile by organisations such as the National Research Centre for Banana (NRCB). As of now, the NRCB has joined hands with the Central Institute of Cotton Technology, Mumbai, with the aim of producing quality fibre. The banana fibre drawn from the stem of the plants is very brittle which makes drawing-out of long fibre a little difficult. The challenges also include the lack of methodology to make the yarns from the fibres. Apart from that, crucial tests like long-term durability of the fabric, retention of fast colour dyeing and stitching capability has to be conducted before the technology can be adopted for commercial production [24]. Only during recent years, banana residue has made into the energy production sector. Successful examples are shown by the banana biogas project by Growcom, Australia and the Compact Biogas Plant which will be discussed later in this paper.

## 3. Methods of energy generation

There are two available methods for conversion of banana biomass into energy, thermal and biological conversion. In this paper, the thermal conversion discussed includes direct combustion and gasification while biological conversion involves anaerobic digestion.

### 3.1. Thermal conversion

#### 3.1.1. Direct combustion

Direct combustion is the burning of biomass directly to convert chemical energy stored in plants into heat and electricity [25].

Usually, biomass is burned in the boiler to produce steam. The pressure of the steam will turn a turbine that is attached to an electrical generator which generates electricity [26]. Currently, there are still no bio-power plants in Malaysia that incorporates banana residue as their biomass feedstock. The potential of banana residue to be directly combusted for energy generation strictly depends on its energy content or heating value. However, the problem lies in that the moisture content of banana residue is very high and this will lead to low energy efficiency. Therefore, better technologies can be utilized to convert banana biomass into energy more efficiently. A better choice would be gasification.

#### 3.1.2. Gasification

Wet biomass grows rapidly and abundantly around the world. Being a wet biomass, banana plants are expected to become one of the renewable energy resources for tomorrow's sustainable society due to their high growth rates and carbon neutrality [27]. However, it is not regarded as a promising feedstock for direct utilization or application for conventional thermochemical gasification processes because of the high moisture content. This problem can be circumvented by employing water as the reaction medium. Namely, in supercritical water gasification of wet biomass (SCWG) is accomplished without having to dry the material and thus, avoiding the high processing costs associated with drying process [28].

SCWG of wet biomass, an advanced technology has drawn attention of a few research groups in the world such as the USA, Germany, Japan and The Netherlands [29]. Supercritical water is water at a temperature higher than its critical temperature (647 K) and a pressure higher than its critical pressure (22.1 MPa), exhibits characteristics between water and steam. Values of density, diffusivity, viscosity for water at supercritical conditions are between those of water and steam, and dependent on temperature and pressure sensitively. Also it is known that supercritical water mixes with most organic compounds, and rapid and homogeneous reactions of organic compounds are possible in supercritical water [30].

A successful SCWG of wet biomass was reported by Matsumura [30]. In that study, water hyacinth was utilized as wet biomass which has a moisture content about 95% and gas composition of the SCWG product was assumed to be at equilibrium for the reaction condition, which is 600 °C, 34.5 MPa. The SCWG process reported is similar to the one proposed before in University of Hawaii [31]. Here, complete gasification to gas composition at equilibrium state was assumed, a salient advantage of SCWG [30]. The heating value of the product gas is calculated to be 20,625 kJ/N $m^3$. Another study was reported in which Yu et al. [32] succeeded in gasification of 0.2 M glucose in supercritical water at 600 °C, 34.5 MPa completely. Xu et al. [33] succeeded in completely gasifying a 1.2 M glucose solution in supercritical water using a carbonaceous catalyst. Matsumura furthered investigated the carbon dioxide separation process applied to supercritical gasification.

The advantages of using SCWG of wet biomass include [34] no drying of wet biomass prior to the process is necessary. In fact, water in wet biomass is essential for the chemical reaction. Apart from that, high yields of hydrogen $H_2$ and very low yield of carbon monoxide (CO) will be obtained compared to the "dry processes" in which synthetic gas produced with CO as the main product. Therefore, additional water–gas-shift process is required to obtain high $H_2$ and low CO for the dry process. With the special properties of supercritical water, less tar and coke will be formed. In SCWG, inorganic ingredients such as salts remain in aqueous solution, thus corrosion problem during gas treatment can be avoided.

In short, SCWG can be a promising technology for gasification of wet biomass such as banana plant since it does not require drying of feedstock beforehand and upon completion of gasification, cooling down and depressurisation of the process will automatically separates the water and gas phase. However, this is an expensive technology and requires more in depth research before it can be carried out commercially. So a more viable option like anaerobic digestion should be considered for the moment.

### 3.2. Biological conversion

#### 3.2.1. Anaerobic digestion

Biological conversion like anaerobic digestion is usually preferred for biomass with high water content. It is a low-temperature process that can process wet or dry feeds (with added water) economically at a variety of scales. The composition of the gas produced is primarily carbon dioxide and methane with small traces of hydrogen sulphide. Fig. 1 shows a general scheme for the anaerobic digestion based on methane fermentation. The biomass (banana residue/waste) are first chopped and grounded to reduce the size and then pretreated to enhance biodegradation. Then, it is either added directly into the reactor or as slurry which is operated at temperature suitable for bacteria growth [35].

There have been some researches conducted on the use of banana waste/residue as the feedstock for methane production through anaerobic digestion. Clarke et al. [20] conducted laboratory studies to measure the methane yield and rate of digestion of reject bananas under the condition that are expected to exist in full scale plants. He demonstrated that there are no technical barriers that exist in the digestion of banana waste at a commercial scale in Australia. The digestion was conducted using fed-batch operation in a 200 l reactor and relies solely on the natural microbial consortia on the reject bananas to avoid dependence on external inocula such as sludge which is not a desirable material around food packaging facilities. The process involves simple technology and requires only simple infrastructure. Clarke's research found that the maximum yield produced were more than 398 l of methane per kilogram of dry banana. With this much amount of methane that is available for energy conversion, 1 tonne of banana waste per day can generate around 7.5 kW of electricity which is about enough to supply six to eight modern households.

Ilori et al. [21] investigated the production of biogas from banana and plantain peels using a 10-l laboratory scale anaerobic digester for a period of 35 weeks. The highest methane generation of 13,356 $cm^3$ was obtained from the combined feedstock of banana and plantain peels while the volume of methane generated from banana peels was 8800 $cm^3$ and from plantain peels, 2409 $cm^3$. Gunaseelan [23] examined the peel of eight different banana cultivars in the standard biochemical methane potential (BMP) test by digesting 0.5 d of powdered sample in 135-ml serum bottles inoculated with sludge from an existing bench-scale digester [20]. He found that the rates of methane production for the banana peels were higher than most of the other fruit wastes. The methane yield obtained was around 266 l per kg dry weight. Bardiya et al. [22] reported a methane yield of 190 l of methane per dry kg of banana peel by operating 2 l anaerobic digesters that were seeded with sludge from a cattle dung digester at a hydraulic residence time (HRT) of 40 days. The yield was higher when the banana peel was dried and powdered, where 201 l of methane per dry kg is obtained.

The results from the literatures above suggest the potential and suitability of banana waste as a feedstock for economically viable waste treatment technology like anaerobic digestion for the purpose of energy generation in the form of methane. However, there is a major limitation to this process due to the incomplete conversion of the organic material where as much as 50% could be left unconverted. Compared to thermal conversion, the process rate is significantly lower and the bacteria involved might require

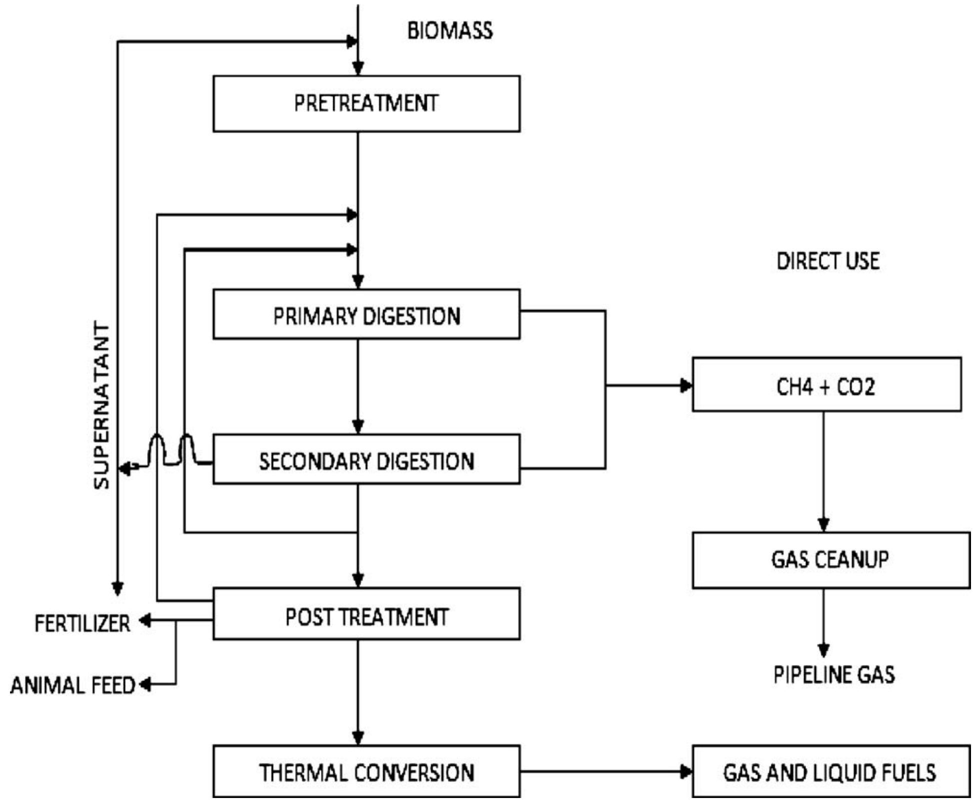


**Fig. 1.** Generalised anaerobic digestion process scheme [35].

nutrients that are not present in the feedstock itself [35]. However, since Malaysia does not have the knowledge and technology to perform biomass gasification, anaerobic digestion is still the most feasible method.

*3.2.2. Indian experience*

In India, the development of Compact Biogas Plant (CBP) [36] by scientist Dr Anand Karve was awarded the prestigious International Ashden Award in 2006. This innovation produce pollution free methane gas and help to conserve planet's depleting fossil fuels uses biodegradable waste as feedstock. One of them is the banana residues such as the peels as India is one of the world's major banana producers. This environment friendly device is installed in an open area closed to housing estates. It has several pipes through which feedstock is added to the fermentor; digested residue removed and generated blue methane biogas travels into the kitchen to a special burner. CBP has helped popularise the conventional Indian practice of using biogas as cooking fuel, albeit in a more efficient manner [36]. CBP can be a life-saving device for those who use indoor biogas stoves. According to the World Health Organisation, about three million people die yearly due to exposure to suspended particle matter in the air, and 85% of those deaths are due to indoor air pollution.

According to Karve, indoor pollution is caused mainly due to traditional cooking stoves, using traditional biomass-based fuels. Use of methane as cooking fuel can prevent these deaths. He further explained the significance of his innovation. Traditionally, biogas is produced from dung. Around 40 kg of dung needs to be fermented for 40 days to produce 250 g of methane. Due to this highly inefficient process, biogas has not emerged as an alternative to LPG. However, his system requires just 1 kg of sugar or equivalent in biodegradable substance to be fermented for 24 h, to produce the same amount of methane. It is this efficiency and uniqueness, as compared to other biogas projects, that earned Karve the Ashden Award which recognises the innovations in sustainable energy.

## 4. Potential energy generation in Malaysia

In order to calculate the potential power generation from direct combustion of banana pseudostem and leaves in Malaysia, the residue/product ratio of the banana plant has to be determined. The residue/product ratio from Yamaguchi and Araki [37] is found to be 2.4 while Jingura and Matengaifa [7] used a ratio of 2. Using the residue/product ratio of 2.4 and an average energy content of 13.1 MJ/kg, the energy potential for the banana residue can be calculated. The potential power was calculated according to the report of Mazlina Hashim [38], where 1 PJ can be converted into 46 MW of electrical energy with 21% electrical conversion efficiency. The banana production for year 2003–2008 [39] and the energy potential of their residue as well as the potential power are shown in Table 1. The amount of potential power generated is in the range of 80–95 MW. For the combustion of banana peels, the residue-to-product ratio of banana peel and the production of banana is taken as 0.25 [40] while the energy content of the banana peel is taken as 18.89 MJ/kg [41]. Similar calculations used previously are used to compute the value of the energy potential and is shown in Table 2.

Besides direct combustion, methane produced from the anaerobic digestion of the banana peels can also be used to generate energy. The same residue/product ratio of the peel is used, while the moisture content of the banana peel is estimated to be around 87% [21]. The biogas is assumed to contain 50% of methane [22]. 1 l of biogas is expected to generate 58.71 mW of energy from combustion in an energy generator [41]. The expected power generation in Malaysia for year 2007 is shown in Table 3.

**Table 1**
Banana residue yield and their potential power generation.

| Year | Yield (kt/year) | Residue/ product ratio | Biomass residue (kt/year) | Residue energy value (MJ/kg) | Energy potential (PJ) | Potential power (MW) |
|---|---|---|---|---|---|---|
| 2003 | 274 | 2.4 | 659 | 13.1 | 8.63 | 83.35 |
| 2004 | 317 | 2.4 | 761 | 13.1 | 9.97 | 96.31 |
| 2005 | 262 | 2.4 | 629 | 13.1 | 8.24 | 79.65 |
| 2006 | 258 | 2.4 | 620 | 13.1 | 8.13 | 78.50 |
| 2007[a] | 265 | 2.4 | 636 | 13.1 | 8.34 | 80.52 |
| 2008[a] | 270 | 2.4 | 649 | 13.1 | 8.50 | 82.13 |

[a] Estimated yield.

**Table 2**
Banana peels yield and their potential power generation.

| Year | Yield (kt/year) | Peel/product ratio | Amount of peel (kt/year) | Energy potential (PJ) | Potential power generation (MW) |
|---|---|---|---|---|---|
| 2003 | 274 | 0.25 | 69 | 1.30 | 12.52 |
| 2004 | 317 | 0.25 | 79 | 1.50 | 14.47 |
| 2005 | 262 | 0.25 | 66 | 1.24 | 11.96 |
| 2006 | 258 | 0.25 | 65 | 1.22 | 11.79 |
| 2007[a] | 265 | 0.25 | 66 | 1.25 | 12.10 |
| 2008[a] | 270 | 0.25 | 68 | 1.28 | 12.34 |

[a] Estimated yield.

**Table 3**
Methane yield for digestion of banana peels and their potential power generation.

| Banana peel | Methane yield (l methane/kg dry banana peels) | Potential power generation (MW) |
|---|---|---|
| Banana peel (chopped) [22] | 190 | 192.24 |
| Banana peel (powdered) [22] | 201 | 203.37 |
| Banana peel (powdered) [23] | 266 | 269.13 |

**Table 4**
Total potential power generation of the banana plant.

| Banana component | Method | Potential power generation (MW) |
|---|---|---|
| Pseudostem and leaf | Direct combustion | 80.52 |
| Banana peels | Anaerobic digestion | 269.13 |
| Reject banana | Anaerobic digestion | 600 |
| | Total | 949.65 |

Compared to the potential power produced from the direct combustion of banana peels ranging from 11.5 to 14.5 MW, the potential power generation of methane from anaerobic digestion gives a much higher value, ranging from 190 to 270 MW. For rejected or rotten bananas, 1 tonne of reject bananas are expected to generate 7.5 kW of electricity [20]. So, for the estimated amount of 80,000 tonnes of rejected and rotten bananas in Malaysia in 2007, power as high as 600 MW can possibly be generated.

Currently, the total available capacity in Malaysia as of the end of 2007 was 20,789 MW, while the electricity consumption was 89,298 GWh [42]. The maximum amount of power that the banana biomass feedstock is capable of generating is estimated to be 950 MW in the year 2007, which is about 4.6% of Malaysia's total available capacity (Table 4). This amount of power generation is not beyond the capability of Malaysia since Malaysia is already quipped with the knowledge and operation of the direct combustion and anaerobic digestion technologies. Direct combustion has been utilized for oil palm residues while anaerobic digestion is widely implemented in wastewater treatment plants all over the country. If the banana biomass is successfully used as the feedstock for energy generation, Malaysia will be able to achieve the target of the Fifth Fuel Policy in which renewable energy contributes 5% of the total energy consumption.

## 5. Advantages of using banana biogas

Bananas give the advantage of producing a very clean form of biogas, consisting of just methane and carbon dioxide as compared to the other waste streams such as human sewage, piggery or feedlot waste, with the added attraction of less noxious odours as well as different trace elements [43]. It also reduce the environmenal issues that the world is now currently dealing with such as global warming and air pollution and it is a clean gas and has a zero carbon cycle. Bananas residues, by products resulting from harvesting and processing and the fruit itself traditionally being discarded due to imperfections which make them unsuitable for sale. These waste normally are dumped in landfills, river, oceans and unregulated dumping grounds forming huge masses of putrefying wastes that attract rodents, insects, scavengers, spread diseases, contaminate water sources and generate fouls odours [44]. This environmental impact can be reduced greatly by converting these residues and waste into banana biogas.

The feedstock for this biogas production can be beneficial to many tropical developing countries not only in Malaysia, but other countries like India, Indonesia and The Phillipines where bananas and plaintains are in abundance either for domestic consumption or exports. With the increasing fuel price and depleting fossil fuels, this technology offers an option for waste management that yields green energy that can contribute to the growth of a county's economy and also a boost to supporting industries such as fertilizer and food production. The banana biogas produced can be used to run tractors, farm machinery and vehicles. This thought of powering communities and vehicles with banana residues may sound a little unrealistic, but University of Queensland researcher and Associate Professor Bill Clarke, shows it is a perfectly feasible option [45]. Thus, reduction in fossil fuel consumption as main energy source can be reduced. Not only that, Dr Clarke demonstrated that there are no technical barries to digesting banana waste at a commercial scale in Australia. Abreast with that, Malaysia has the potential to convert banana residues to energy as the process requires simple infrastructure, the feedstock is easy to be handled and has a high yield of methane biogas.

## 6. Challenges ahead

Even though banana residue or waste provides quite a high power generation, there are some issues involved in recovering the feedstock, storage problems, financial and technical challenges. The availability of the banana crop residue for energy purposes has been addressed in several studies. The critical issue here is to determine the amount of residue that is available for energy use. It is important to first estimate the amount of residues that are used for animal feed and also those that are retained in the field to prevent erosion and provide nutrients. Thus, in certain studies, some coefficients that take into account the minimum amount of residues used for agricultural purposes have been developed to transform the crop residues data into data that are more suitable and applicable for the sole purpose of energy use calculation [7]. Another issue lies in the collection of banana peels from the industry and residential home. A good system needs to be implemented so that most of the banana peels can be collected and sent to the biogas plant.

Another challenge involves finding the best technology to overcome the long-term storage problem of banana biomass. The moisture content of the feedstock affects all supply chain elements such as collection, storage, pre-processing, handling and transportation [46]. The banana waste and residue are highly biodegradable because of their rich organic matter and high moisture content [22]. Such high moisture content might cause instability of the biomass material because it biodegrades easily with the action of microbes. This can cause problems with dry-matter loss and hygiene due to the release of the pungent odor and fungi production [47]. So, the drying of the wet biomass is very important. However, an optimum supply system should be used to balance the cost of handling and storing the banana waste against the cost of removing the moisture and pre-processing the material to a uniform handling format [43].

There are some financial and technical barriers in the production of energy from banana biomass. The use of technologies like SCWG is quite expensive and needs high initial investment. Malaysia has very limited equipment and lack proper technical knowledge to implement this method. Poor financial support from the Malaysian government discourages researchers and developers from practicing this technology [48]. This issue is not just limited to the practice of new technology, but also the ones that are already present in Malaysia. The renewable energy (RE) projects that were implemented in year 2006 were initially supported financially, but the support was not continued for the coming year [49]. This impedes the operations of these RE projects. There should have been a long-term plan for the implementation of these projects and continuous monitoring should be done to ensure that the project is financially capable to run.

## 7. Conclusion

Malaysia is aiming to become a developed nation by 2020. To meet such a growing demand of energy, alternative energy resources like biomass should be considered as the fossil fuel might only last for another half of a century. For the time being, palm oil biomass dominates the scenario. However, this might cause the monopolisation of certain industries due to the over dependence on a single source. Banana plants can be part of the renewable energy resources for tomorrow's sustainable society due to their high growth rates and carbon neutrality. This paper also deals with the energy potential generated by banana plant biomass in Malaysia. From the result and discussion carried out, a maximum power of 80.52 MW can be obtained from direct combustion and 869.13 MW from anaerobic digestion, giving rise to an estimate of 949.65 MW. As regarded in the Fifth Fuel Policy, renewable energy was announced as the fifth fuel in the energy supply mix aiming to make up 5% of the nation's total energy consumption [50]. Meeting around 4.6% of the total available capacity in Malaysia for the year 2007, banana biomass energy has made up to more than half of the renewable energy requirement. Hence, it is feasible to use banana plant biomass as a source renewable energy locally.

## Acknowledgements

The authors would like to acknowledge Universiti Sains Malaysia (Research University Grant No.1001/PJKIMIA/814047 and USM Fellowship) for the financial support given.

## References

[1] National Center for Atmospheric Research (NCAR) Climate Research. Climates of the future; 2008. Available at: http://www.ncar.ucar.edu/research/climate/future.php.
[2] Parry M, Arnell N, McMichael T, Nicholls R, Martens P, Kovats S, et al. Millions at risk: defining critical climate change threats and targets. Available at: http://ncsp.va-network.net/UserFiles/File/PDFs/Resource%20Center/Water%20re-sources/60_Parry_Global%20climate%20change%20impacts.pdf.
[3] Thomas CD, et al. Extinction risk from climate change. Nature 2004;427:145–8.
[4] International Scientific Steering Committee. International symposium on the stabilisation of greenhouse gas concentrations. Avoiding dangerous climate change; 2005. Available at: http://www.stabilisation2005.com/Steering_Commitee_Report.pdf.
[5] Fanchi JR. Energy technology and directions for the future. Elsevier; 2004. p. 213.
[6] International Energy Agency (IEA). Key World Energy Statistics; 2007. Available at: http://www.iea.org/textbase/nppdf/free/2007/Key_Stats_2007.pdf.
[7] Jingura RM, Matengaifa R. The potential for energy production from crop residues in Zimbabwe. Biomass and Bioenergy 2008;32:1287–92.
[8] Biopact. Growcom trials commercial biogas production from banana waste—high potential yields; 2008. Available at: http://news.mongabay.com/bioenergy/2008/01/growcom-trials-commerical-biogas.html.
[9] Mohamed AR, Lee KT. Energy for sustainable development in Malaysia: energy policy and alternative energy. Energy Policy 2006;34:2388–97.
[10] Malaysian Palm Oil Board (MPOB); 2009. Available at: http://www.mpob.gov.my/.
[11] Friends of the Earth. The oil for ape scandal; 2005. Available at: http://www.foe.co.uk/resource/briefings/palm_oil_biofuel_position.pdf.
[12] Domingo NC, Ferraris FV, Del Mundo RR. Technology State of the Art in SEA; 2003. Available at: http://www.ec-asean-greenippnetwork.net/documents/tobedownloaded/knowledgemaps/KM_status_tech_SEA.pdf.
[13] Ramirez A. To grow bananas. CRFG Fruit Gardener; 1995. Available at: http://www.kalron.com/kalstor/pub/crfg/banana-crfg-v27-5.htm.
[14] Abdul Khalil HPS, Siti Alwani M, Mohd Omar AK. Chemical composition, anatomy, lignin distribution and cell wall structure of Malaysian plant waste fibers. BioResources 2006;17:220–32.
[15] Morton JF. Fruits in warm climates: banana. Available at: http://www.hort.purdue.edu/newcrop/morton/banana.html#Harvesting.
[16] SNH GROUP. Agriculture Industry Malaysia. Available at: http://www.snhgroup.myportal.my/?lang=my&act=5&content=48&id=3&mnu=3.
[17] Asia Source; Asia Food; Banana Plant. Charmaine Solomon's Encyclopedia of Asian Food. New Holland Publishers (Australia) Pty Ltd: Periplus Editions; 1998.
[18] Wikipedia, The Free Encyclopedia. Banana, Botany. Available at: http://en.wikipedia.org/wiki/Banana.
[19] Biopact news. Banana biofuels; 2006. Available at: http://news.mongabay.com/bioenergy/2006/09/banana-biofuels.html.
[20] Clarke WP, Radnidge P, Lai TE, Jensen PD, Hardin MT. Digestion of waste bananas to generate energy in Australia. Waste Management 2008;28:527–33.
[21] Ilori MO, Adebusoye SA, lawal AK, Awotiwon OA. Production of biogas from banana and plantain peels. Advances in Environmental Biology 2007;1(1):33–8.
[22] Bardiya N, Somayaji D, Khanna S. Biomethanation of banana peel and pineapple waste. Bioresource Technology 1996;58:73–6.
[23] Gunaseelan N. Biochemical methane potential of fruits and vegetable solid waste feedstocks. Biomass and Bioenergy 2004;26:389–99.
[24] Fibre2fashion News Desk – India. Banana Fibre – The Next New Sensation in Textile Industry; 2008. Available at: http://www.fibre2fashion.com/news/textile-news/newsdetails.aspx?news_id=62147.
[25] Clini C, Musu I, Gullino ML, editors. Sustainable development and environmental management: experiences and case studies. Springer; 2008. p. 228–9.
[26] Chambers A. Renewable energy in nontechnical language. PennWell Books; 2003.
[27] Matsumura Y, Kato A, Sasaki H, Yoshida T. Progress in thermochemical biomass conversion, vol. 1, IEA Bioenergy. In: Bridgewater AV, editor. Google E-books. p. 237–8.
[28] Matsumura Y, Minowa T, Xu X, Nuessle FW, Adchiri T, Antal Jr MJ. Development in thermochemical biomass. In: Bridgewater AV, editor. Kluwer Academic Publishers; Google E-book. p. 864–70.

[29] Van Swaaij WPM, Matsumura Y, Prins W, Minowa T, Antal Jr MJ. Technical feasibility of biomass gasification in fluidized bed with supercritical water. Available at: http://www.nedo.go.jp/itd/grant-e/report/00pdf/gp-01e.pdf.
[30] Matsumura Y. Evaluation of supercritical water gasification and biomethanation for wet biomass utilization in Japan. Energy Conversion and Management 2002;43:1301–10.
[31] Matsumura Y, Minowa T, Xu X, Nuessle FW, Adschiri T, Antal Jr MJ. High-pressure carbon dioxide removal in supercritical water gasification of biomass. In: Breidgwater AV, Boocock DGB, editors. Developments in thermochemical biomass conversion, vol. 2. Blackie Academic & Professional; 1997 p. p.864–77.
[32] Yu D, Aihara M, Antal MJ. Hydrogen production by steam reforming glucose in supercritical water. Energy Fuels 1993;7:574–7.
[33] Xu X, Matsumura Y, Stenberg J, Antal Jr MJ. Carbon-Catalyzed Gasification of Organic Feedstock in Supercritical Water. Industrial & Engineering Chemistry Research 1996;35:2522–30.
[34] Gasafi E, Reinecke M-Y, Kruse A, Schebek L. Economic analysis of sewage sludge gasification in supercritical water for hydrogen production. Biomass and Bioenergy 2008;32:1085–96.
[35] Chynoweth DP, Isaacson R. Anaerobic digestion of biomass. Springer; 1987.
[36] Gagandeep Kaur. The Biogas Kitchen. The Hindu Business Line, Business Daily from THE HINDU group of publications; 2007. Available at: http://www.blonnet.com/life/2007/01/26/stories/2007012600110200.htm.
[37] Yamaguchi J, Araki S. Biomass production of banana plants in the indigenous farming system of the East African Highland: a case study on the Kamachumu Plateau in northwest Tanzania. Agriculture Ecosystems and Environment 2004;102:93–111.
[38] Mazlina Hashim, Present Status and Problems of Biomass Energy Utilization in Malaysia. Tokyo and Tsukuba: APECATC – Workshop on Biomass Utilization; 2005. Available at: http://www.igloo.org/libraryservices/download-nocache/Library/subjects/sciencet/sciencet~1/energy/presents.
[39] Department of Agriculture Malaysia. Available at: http://www.doa.gov.my/statistik/buah03-08.htm.
[40] Wilaipon P. The effects of briquetting pressure on banana-peel briquette and the banana waste in northern Thailand. American Journal of Applied Sciences 2009;6(1):167–71.
[41] Nelson C, Lamb J. Final report: Haubenschild farms anaerobic digester. The Minnesota Project 2002. Available from World Wide Web: http://www.mnproject.org/pdf/Haubyrptupdated.pdf.
[42] Malaysia Energy Database and Information System. Energy Info Highlights; 2008. Available at: http://medis.ptm.org.my/highlights.html.
[43] Biopact news. Banana biogas to power, heavy-duty farming equipment and vehicle; 2006. Available at: http://news.mongabay.com/bioenergy/2006/10/banana-biogas-to-power-heavy-duty.html.
[44] Wood MT, Tabora P, Gabert L, Hernandez C, Miles R. Sustainable treatment of banana industry and crop residue wastes for crop production using effective microorganisms (EM). Effective Microorganism @ Emtrading.Com. Available at: http://emtrading.com/em/papers/embanana.pdf.
[45] Biopact news. Growcom trials commercial biogas production from banana waste—high potential yields; 2008. Available from World Wide Web: http://news.mongabay.com/bioenergy/2008/01/growcom-trials-commerical-biogas.html.
[46] IdeaConnection. Biomass moisture management and material stabilization. Available at: http://www.ideaconnection.com/technology-wanted/459-Biomass-Moisture-Management-and-Material-Stabilizatio.html.
[47] Van Loo S, Koppejan J. The handbook of biomass combustion and co-firing. Earthscan; 2008. p. 79.
[48] Hassan MA, Yacob S, Abdul Ghani B. Utilization of biomass in Malaysia: potential for CDM business. Available at: http://www.jie.or.jp/pdf/16.Prof.Hassan.pdf.
[49] Federation of Malaysian Consumer Associations (FOMCA). Memorandum: State of Energy and Consumers; 2007. Available at: http://fomca.org.my/bmalay/UserFiles/File/1%2520Memorandum%2520State%2520of%2520Energy%2520and%2520Consumers-bm.pdf.
[50] World Resources Institute (WRI). Energy Policy in the 8th Malaysia Plan/Five Fuel Policy on the article "Malaysia: Energy Policy in the 8th Malaysia Plan/Five Fuel Policy". Available at: http://projects.wri.org/sd-pams-database/malaysia/energy-policy-8th-malaysia-plan-five-fuel-policy.